Smart Acoustic Network Using Combined FSK-PSK, Adaptive Beamforming and Equalization

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LONG-TERM GOALS

Our long-term objective is a smart acoustic network for multiple underwater vehicle operation, with integrated communication and positioning capability. To do so, a new generation of Coherent Path Beamformer would act as a network decoder and arbitrator for data communication and long (short) base line. Also, wireless communication to shore would be available for control and real-time data transfer. Finally, the underwater vehicles will be carrying an improved version of the compact low-cost Acoustic Modem. This concept requires the network to be synchronous. The concept is to make the most efficient use of time and frequency band.

OBJECTIVES

The smart acoustic network is a multiple-layer system that achieves distinct tasks. As a result, our research effort has been divided into three main projects:

1. High-speed acoustic communication using a High Performance Acoustic Link (FAU-HPAL, Figure 1), also know as "MillsCross".
2. High-reliability acoustic network using multiple General Purpose Acoustic Modems (FAU-GPAM, Figure 2), with a monitoring option using the FAU-HPAL.
3. Development of a Dual-Purpose navigation/telemetry Acoustic Modem (FAU-DPAM, Fig. 3-4).

The two-year objectives for the high-speed acoustic communication project, using a High-Performance Acoustic Link (FAU-HPAL), are as follow:

1. Setup real-time signal processing software and hardware development and testing for the FAU-HPAL communication system (MillsCross).
2. Upgrade current FAU-GPAM software/hardware for optimal high and low-speed communication.
3. Run communication tests in conjunction with SFOMC Shallow Water MUX facility.
4. Achieve high-rate video and sonar data transmission from underwater vehicle during mission.

The two-year objectives for the high-reliability acoustic network using multiple General-Purpose Acoustic Modems (FAU-GPAM), with a monitoring option using the FAU-HPAL, are as follow:

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14. ABSTRACT
Our long-term objective is a smart acoustic network for multiple underwater vehicle operation, with integrated communication and positioning capability. To do so, a new generation of Coherent Path Beamformer would act as a network decoder and arbitrator for data communication and long (short) base line. Also, wireless communication to shore would be available for control and real-time data transfer. Finally, the underwater vehicles will be carrying an improved version of the compact low-cost Acoustic Modem. This concept requires the network to be synchronous. The concept is to make the most efficient use of time and frequency band.

15. SUBJECT TERMS

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1. Achieve reliable communication with the current FAU-GPAM generation in underwater vehicle conditions of operations (2000 meters max, mode 4 dual Viterbi/BCH or Reed-Solomon).

2. Design the third generation of FAU-GPAM with the following features:
   a) Smaller size and average power use, better multiple ADC/DAC, low electrical noise, Ethernet.
   b) New transducer with broader frequency band for multiple mode support.
   c) Multiple receivers for channel diversity.
   d) Greater processing power, improved multi-channel signal processing.

3. Monitor the underwater vehicle network using FAU-HPAL in FSK mode.

APPROACH

High-Speed Acoustic Communication using FAU-HPAL:

Underwater acoustic communication is vital to the operation of Autonomous Underwater Vehicles (underwater vehicle) and transmission of data from remote underwater imaging sensors. Over the past decade, many programs have been put in place to develop coherent high-speed underwater acoustic communication. We have developed a high performance acoustic link called the FAU-HPAL, using a multi-element receiver array that provides 64 individual signals to a high-resolution analog-to-digital converter and digital storage system[1-8]. The source is the FAU General Purpose Acoustic Modem (FAU-GPAM) developed at FAU (sonar laboratory) and used for acoustic networking during underwater vehicle operation. The joint adaptive coherent path beamformer method consists in splitting the space and time processing into two separate sub-optimal processes. As a result, processing complexity is significantly reduced and the instabilities associated with large tap vectors at large time-frequency spread products are reduced. This method utilizes a different beamformer optimization strategy compared to the time domain optimization strategy, and allows to separately adjust the adaptation parameters for the spatial and temporal characteristics of the signal, which have vastly different requirements. The time domain signal is subject to variations in phase that require rapid filter updates whereas the directional characteristics of the signal do not vary appreciable over the message length and do not require a rapid adaptation response. This method allows for high-speed underwater acoustic communication in very shallow water using coherent modulation techniques, and offers a series of unique features: significant reduction of the signal-to-noise and interference ratio (SNIR), improvement of the bandwidth efficiency by reduction of the forward-error coding redundancy requirements, real-time evaluation of the time-spread by Doppler-spread product (BL) and channel stability estimate.

Acoustic Network using multiple FAU-GPAM and FAU-HPAL Monitoring:

The FAU-GPAM is a high reliability shallow water acoustic modem developed for communication between underwater vehicle and general oceanographic use[9-11]. The modem uses 56 narrow band chirp FM pulses, each centered at a unique frequency located in the range of 16 kHz to 32 kHz. Data rates vary from 221 data bits per second to 1172 data bits per second, depending on the mode of transmission. Packets of information are synchronized using an adjustable number of chirp pulses in a known frequency hop pattern, followed by transmission format information and data. An “auto-baud”

mode uses information garnered from previous transmissions for adaptation of the bit rate to the acoustic environment. At the lowest rate, a four-time slot frequency hop pattern is used to provide maximum immunity to multipath interference. The modem is capable of using both half rate convolutional and BCH encoding in order to maximize error resilience. As a first step toward monitoring of the acoustic network using the FAU-HPAL, a multiple-channel signal-processing algorithm has been developed to decode frequency-hopped frequency-shift-keyed (FH-MFSK) FAU-GPAM signals acquired by the MillsCross receiver. This process includes a robust synchronization scheme, a spatial filter as well as a time-window self-adjusting process and error-control decoding. The synchronization process requires that a message is present when 6 bins are good out of 8 which gives 9.10^{-8} probability of false alarm. When it occurs, the time acquisition window is adjusted and the selected signals are combined again. The spatial filter used in this software is an equal gain combiner method. The FFT and the matched-filter are done separately on each channel. The envelope of each spectrum is added which helps for the decision making. This method efficiently overcomes the effect of frequency fading, and gives a nearly 9 dB signal-to-noise ratio for the mode 4 at 5 kilometers. This program includes decoding algorithms for BCH, Reed Solomon, Viterbi and dual modes.

Dual-Purpose Acoustic Modem for Telemetry and Synchronous Navigation

The FAU-DPAM is a high reliability shallow water acoustic modem developed for communication between underwater vehicle and general oceanographic use. FAU-DPAM underwater acoustic modem is the second generation of modems developed at Florida Atlantic University. This new modem is being developed to meet current and future requirements in the underwater communications and underwater vehicle fields. The modem provides a robust communications system as well as a versatile platform for research and development of new underwater acoustics and communications techniques. The acoustic modem provides a wireless underwater communications link in the frequency band of 15 to 35 kHz. The host processor handles message traffic to and from the user, formats data to and from the digital signal processor (DSP), time tags incoming and outgoing messages and manages various system resources. The digital signal processor modulates/demodulates messages in the communication channel and manages channel access. The power amplifier drives a broadband communications transducer, while the low noise preamplifier conditions received signals for analog to digital conversion. External user RS232/RS422 serial and 10Base-T Ethernet interfaces are available for host processor communications. Additionally, the host processor address/data bus, host processor SPI serial bus, and DSP multi-channel buffered serial port are available to external devices. The acoustic modem has been designed for maximum system flexibility. The host processor enables the user to easily reconfigure the modem for different communication needs while a powerful fixed point DSP (160 MIPS) allows the implementation of sophisticated encoding/decoding schemes. New features of the modem include:

- Bi-directional data rates up to 2400 bps, high-speed data transmission at rates up to 32000 bps.
- Multiple receiver hydrophones for spatial diversity.
- Integrated or remote tuned broadband transducer. Special attention has been taken about the design of the FAU-DPAM reciprocal transducer, including numerical modeling[13] and measurements in collaboration with International Transducer Corporation.
- Message time tagging, synchronizable to external GPS system and optional low drift time base.
- On board memory for data logging.

- ♦ Multiple user interfaces.
- ♦ Small size, Low power design for extended operation.

WORK COMPLETED (October 1st 2000 to September 30th 2001)

High-Speed Acoustic Communication using FAU-HPAL:

1. Joint adaptive coherent path beamformer processing of experimental data collected half-mile off Fort Lauderdale coast using the FAU-HPAL and FAU-GPAM: up to 3.5 km range, 20'-40' water depth, sand and reef Bottom, 0 to 3 knots source speed, reverberation time over 20 ms.
2. FAU-HPAL has been equipped with batteries for standalone operation (Figure 1).
3. Integration of the second generation of 64-channel acquisition system is completed. This new system can sustain 128000 samples/second/channel in continuous acquisition mode (Figure 1).
4. FAU-HPAL is ready for SFOMC operation.

Acoustic Network using multiple FAU-GPAM and FAU-HPAL Monitoring:

1. Two FAU-GPAM have been supplied to the Naval Postgraduate School and mounted on the Aries UUV for at-sea operation (Figure 2).
2. The FAU-GPAM has been extensively tested during at-sea testing on underwater vehicle platforms. It has been intensively tested during the development of the FAU-OEX-C UUV.
3. The FAU-HPAL has been used to monitor two FAU-GPAM acoustic communication using boat platform, both at sea and in noisy harbor environments (Port Everglades).

Dual-Purpose Acoustic Modem for Telemetry and Synchronous Navigation

Three prototypes have been assembled and tested in the intra-coastal waterway (Figure 3 and 4). These prototypes have the following features:

- Single transmitter/multiple receiver for spatial diversity (communications).
- Low-drift GPS clock for navigation.
- Frequency band: 15-35 kHz transmit/receive (used), 12-35 kHz transmit max, 4-35kHz receive max.
- Bi-directional data rate (FH-MFSK):
    - 220 to 1181 bps (2363 bps under work)
    - High-Speed Transmission: 32000 bps max (MPSK, MillsCross receiver) .
- Navigation Accuracy: 600 microsec. or 1 meter.
- 2 serial ports (RS232 or 422), 10Base-T Ethernet.
- Size:6"x2"x1.5" (Electronics), 2"x3"(Assembly).
- Power: 50 mW (standby), 600mW (4 channels receiver mode), 50 W at 187dB (transmit mode).

RESULTS (October 1st 2000 to September 30th 2001)

High-Speed Acoustic Communication using FAU-HPAL:

1) Using this multiple-stage method, bit rates of 32000 bps can be achieved over 3000 meters range. Better reliability is expected with the new hardware at this rate.
2) Practical rates of 8000 bps to 16000 bps are achieved with high reliability using current hardware.
3) Experimental data collected half-mile off Port Everglades using FAU-HPAL and FAU-GPAM:
   a) up to 3.5km range, 20'to 40' water depth, Sand and Reef Bottom
   b) 0 to 3 knots source speed, Reverberation Time over 20 ms
4) Communication performance measured as Bit Error Rate (BER):
   a) BPSK,125 μs symbol, 8000 bps, SNR 15 dB, BER < 0.01%.
   b) QPSK,125 μs symbol, 16000 bps, SNR 15 dB, BER < 0.5%.
   c) BPSK,125 μs symbol, 16000 bps, SNR 12 dB, BER < 0.5%.
   d) QPSK,62 μs symbol, 32000 bps, SNR 12 dB, BER < 10%.
5) Experimental results demonstrate that stable acoustic communication can be achieved at rates of 32000 bits per second at a distance of 3 km, in 40 feet of water and in sea-state 2 conditions. Fast and slow fading properties of the channel are measured, as the BL product can vary by a decade in 116 ms, and by two decades within minutes, from 0.001 to 0.1 (Figure 5 to 8). The real-time analysis shows a strong correlation between time spread, Doppler spread, spatial coherence of the acoustic channel and communication performance. The high-speed communications research also provides more scientific and experimental ground to understand the limitations of multi-channel adaptive receiver techniques in terms of stability, hardware requirements and channel tracking capability (Figure 5 to 8).

High-Reliability Acoustic Network using multiple FAU-GPAM and FAU-HPAL Monitoring:

The FH-MFSK communication performance was measured in terms of data Frame Error Rate (FER), more relevant for this type of application. The following experimental results have been obtained:

1. underwater vehicle conditions of operations exceeded, even in single BCH mode:

a) mode 4 (BCH, 221 bps) works up to 5000 meters with 40% FER (9 dB SNR)

b) mode 4 (BCH, 221 bps) works up to 2500 meters with 1.6% FER (16 dB SNR)

c) mode 3 (BCH, 443 bps) works up to 2500 meters with 25% FER (16 dB SNR)

2. FAU-HPAL in FSK mode provides significantly better results:

a) mode 4 (BCH, 221 bps) works up to 5000 meters with 0% FER

b) mode 3 (BCH, 443bps) works up to 4000 meters with 0% FER

c) mode 2 (BCH, 866 bps) works up to 4000 meters with 0% FER

d) mode 1 (BCH, 1181 bps) works up to 3000 meters with 0% FER

IMPACT/APPLICATIONS

Experimental results are providing a new insight to the understanding of how shallow water propagation conditions affect the information capacity of digital data transmission for sonar operating in the frequency range of 25 kHz. Millions of data bits encoded using PSK and FSK have been transmitted at distances exceeding five kilometers over a moving platform. Error rates, adaptation time constants, and the influence of the environment on the stability of the various modes of propagation are inferred. Principal component analysis of the received data using moving platforms has also provided an important insight into the frequency smear of each of the various multipath receptions. This information is invaluable in generating models for use in testing acoustic modem designs and high-rate data transmission in shallow water environment. The MFSK modem proves that use of multiple frequency channels and frequency-hoping technique are suited for multiple-users underwater communication. Finally, the acoustic navigation/telemetry buoy design allows for accurate navigation without interfering with the regular acoustic communication mode. The fusion of these three techniques (FAU-HPAL, FAU-GPAM and FAU-DPAM) is the next step for a fast and reliable underwater acoustic network.

TRANSITIONS

The current generation low-cost single channel modem that uses Gaussian spread spectrum wavelets with compensation and the associated hardware has been successfully transitioned to a commercial oceangraphic instrumentation company: Edgetech Inc. is currently manufacturning the single-channel modems (GPAM). The new generation of dual purpose acoustic modem has been disclosed to FAU and is expected to follow a very similar path in 2002.

RELATED PROJECTS

The Smart Acoustic Network project has three important objectives: high-speed acoustic communication, high-reliability acoustic networking and combined navigation/telemetry. This lead us to develop tools for obtaining a better understanding of the underwater acoustic channel in shallow water. Success in these objectives will be extremely beneficial to other projects in the ONR AOSN effort as well as other Navy objectives in shallow water acoustics.

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Figure 1. FAU High-Performance Acoustic Link (FAU-HPAL or "MillsCross")

Figure 2. General Purpose Acoustic Modem (GPAM) and Aries UUV Platform

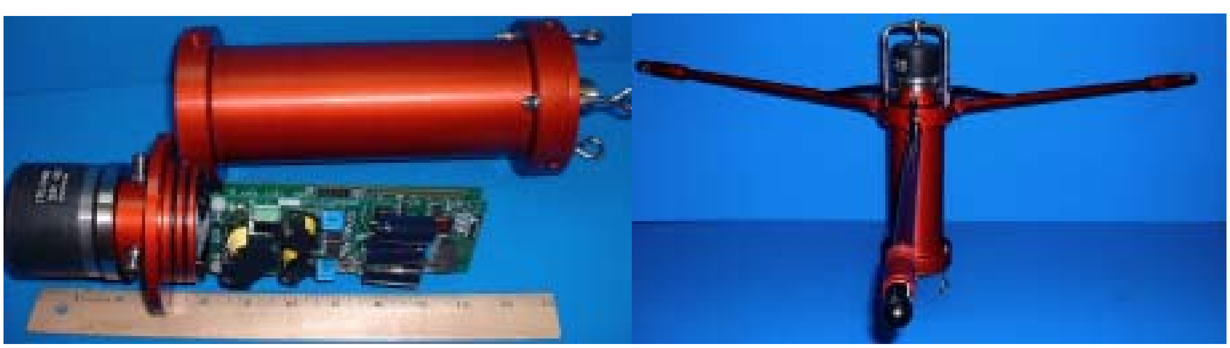

Figure 3. Dual Purpose Acoustic Modem (DPAM) for Communication and Navigation

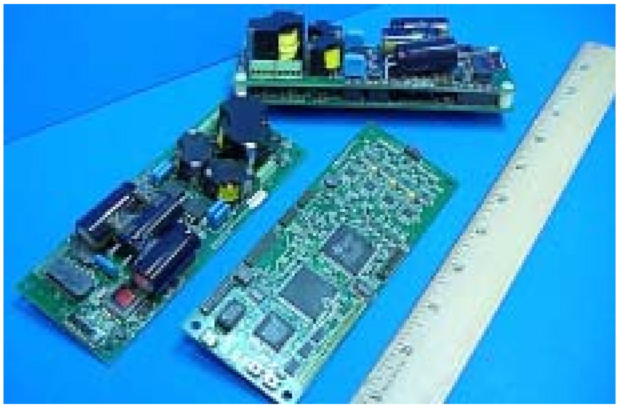

Figure 4. Dual Purpose Acoustic Modem (DPAM) Embedded Electronics

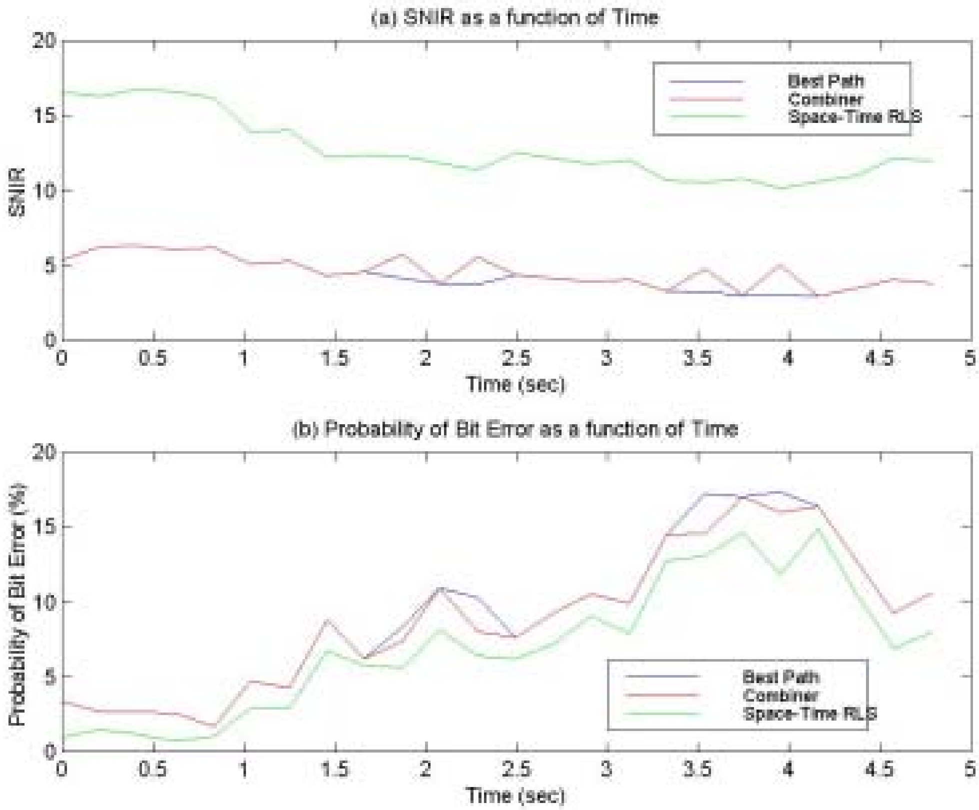

Figure 5. Demodulation Performance in the 16kHz-32kHz Band, Measured over 24 125μs-QPSK Modulated Packets, in terms of (a) SNIR and (b) BER.

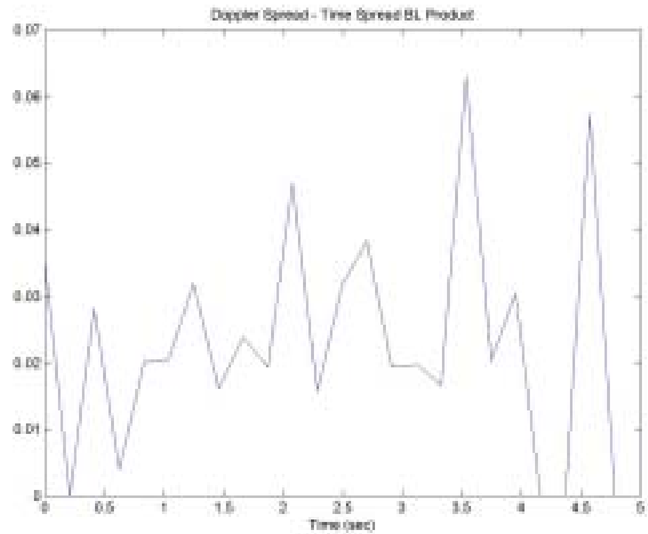

Figure 6. Time Spread – Doppler Spread BL measured in the 16kHz-32kHz Band, every 183 ms during the 125μs-QPSK Modulated Message Transmission.

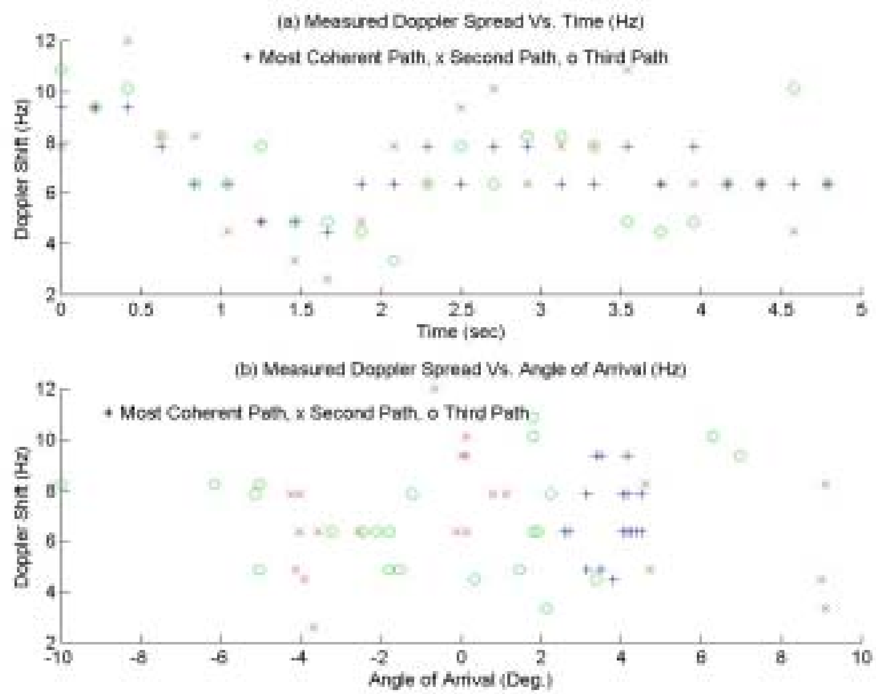

Figure 7. Acoustic Channel Frequency-Space Profile in the 16kHz-32kHz Band, Measured every 183 ms during the 125μs-QPSK Modulated Message Transmission, in terms of (a) Coherent Paths Doppler Shift Vs. Time, (b) Coherent Paths Doppler Shift Vs. Angle of Arrival.

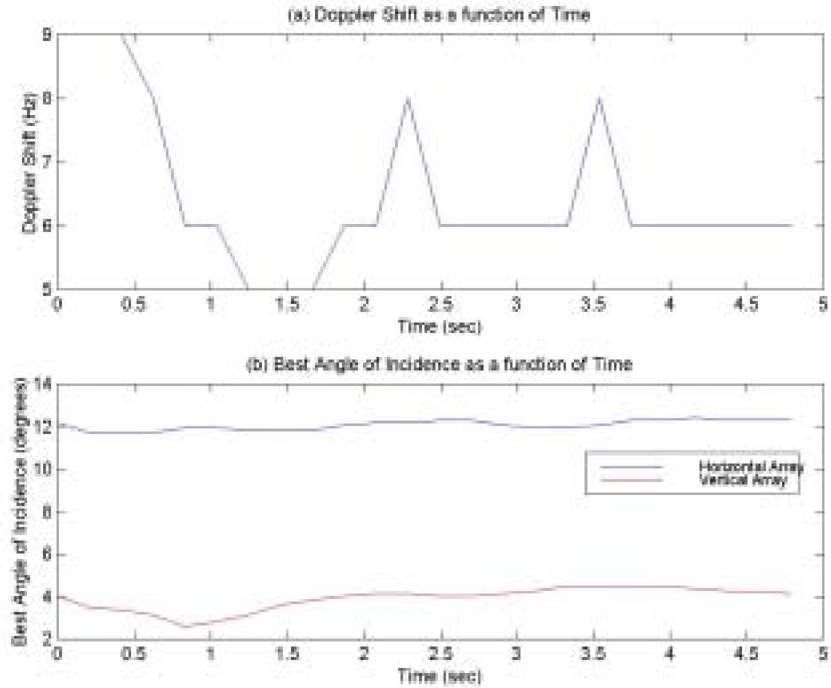

Figure 8. Acoustic Channel Time-Space Profile in the 16kHz-32kHz Band, Measured every 183 ms during the 125μs-QPSK Modulated Message Transmission, in terms of (a) Time-Spread, (b) Energy Distribution.